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Challenges and developments of bioretention facilities in treating urban stormwater runoff; A review

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ABSTRACT: Bioretention or rain garden is a preferable low impact development (LID) approach due to its characteristics which reflect natural water cycle processes. However, this system is still little understood and quite complicated in terms of design and implementation due to many technical considerations. Hence, this paper gives a review of the challenges and developments for the use of bioretention facilities to enhance its capabilities in attenuating peak flow and treating stormwater runoff particularly in urban areas. This paper reviews the main aspects of bioretention which are stormwater hydrologic, hydraulic and treatment performance. Some of the limitations during the implementation of this natural approach are highlighted in design configuration and the public perception towards this new approach. It is concluded that the bioretention approach is one of the sustainable solutions for stormwater management that can be applied either for individual systems or regional systems.

Keywords: bioretention, hydrologic performance, infiltration practices, treatment performance.

INTRODUCTION

In recent decades, rapid urban development in developing countries has inflicted major environmental problems on natural systems, mainly flash flood and sustainability of the stormwater system (Chan, 2013). Unplanned urbanization inevitably results in significant increment of impervious surface area in urban areas (Al-Hamati et al., 2010), thereby changing the hydrological cycle, water quality performance significantly (Shuster et al., 2005), as well as ecosystem (Fletcher et al., 2014). These processes in the hydrological cycle are disturbed by such rapid urban development (Li et al., 2009). Hence, the main solution to tackle this issue is to understand and mitigate the consequences of urbanization matters on urban hydrology and stormwater quality (Liu et al., 2014).

Research results have shown that bioretention is recommended as one of the promising tools to minimize the impact of urban runoff by incorporating water quality improvement as well as reduction of runoff volume from impervious catchment areas (Le Coustumer et al., 2012). This system is possibly one of the most cost effective and sustainable integrated management

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practices in low impact development approach using soil mixture to control flow with a highly effective filter media for stormwater pollutants (Davis et al., 2001).

Thus, governments and private agencies have taken proactive steps to ensure that all development must provide a holistic approach by considering the environmental impact in developing areas in order to make urbanization and environmental issues to be in balance or steady state condition. The guidelines are to be mandatorily carried out to all parties involved such as planners, developers, architects, consulting engineers, and contractors to provide the best design solutions for the betterment of life. In the United States and Australia, concepts such as Low Impact Development (LID) and Water Sensitive Urban Design (WSUD) were introduced as guidelines of stormwater management practices. Furthermore, in European countries and the United Kingdom, the Best Management Practices (BMPs) and Sustainable Urban Drainage System (SUDs) have been applied for many years when dealing with stormwater runoff. It is also known as Stormwater control measures (SCMs) (Jenkins et al., 2010). Urban Stormwater Management Manual for Malaysia or "Manual Saliran Mesra Alam Malaysia" (MSMA) was introduced as guidelines for Malaysia with similar objectives since the early 21st century. The aim of these stormwater management concepts are to encourage new sustainable urban development associated with natural process such as integrating hydrological cycle in the urban system. For example, housing development can be built in more greenery areas by providing a systematic drainage system and promoting more pervious areas that allow infiltration, transpiration and other hydrological processes which can be fitted into the system.

One of the possible approaches is bioretention. It is also known as rain garden which consists of porous media, mulch and vegetation elements (DeBusk & Wynn, 2011). The term bioretention came from the combination of two words, "bio-mass" and "retains" (Coffman & Siviter, 2007). Physically, it looks like a beautiful garden full of various species of vegetation and flowers on the ground surface. Surprisingly, this system can provide runoff treatment system as well as flow attenuation through natural process. Besides, it is also promoting bio-ecological system by having insects, birds and others. Technically, it is also referred as cost effective stormwater management tools with shallow excavation designed to filter and store stormwater runoff (LTU, 2011). Bioretention is one of the stormwater control measures (SCMs) that consist of an excavated basin with installation of soil filter media and vegetated plant (Lucas, 2010). In addition, DID (2012) referred bioretention as one of BMPs forms which apply the combination of biological uptake and filtration process through porous media to treat stormwater runoff (DID, 2012). Bioretention system is applicable at various places. It can be designed for smaller drainage areas such as from single lot to larger scale development areas to collect the runoff from parking lots or high-rise building rooftops (Davis and McCuen, 2005). Besides, it is also designed to address runoff from the roads and streets where it is located at both sides of the streets or road dividers.

Rain garden can be proposed as permeable and impermeable (DID, 2012). A pervious or permeable system carries runoff through fill media in a certain rate and passes through sand bed layer. This system promotes exfiltration process due to the absence of subdrains installation and also encourages groundwater recharge (Estes, 2007). Finally, its balance is discharged as the outflow. Impermeable system has different configuration of its outflow zone. The perforated pipe or subsoil pipe is installed underlying filter media. The infiltrated water is captured by this pipe and is transported to the existing conveyance or natural receiving watercourse. An advantage of this system is that it will provide the capacity for the next storm event due to the presence of underdrain which can convey outflow in a shorter period of time compared to the pervious system.

Hence, this paper reviews the development, experiences and issues of bioretention facilities in enhancing its performance and providing more sustainable infrastructures to the society and nation.

CHALENGGES AND ISSUES IN BIORETENTION IMPLEMENTATION

Bioretention is typical Low Impact Development (LID) practice to adopt natural hydrologic process, pollutant removal and aesthetic values (Brown and Hunt III, 2011). Bioretention offers multiple solutions in dealing with stormwater runoff. Based on the criterion of this system, it can provide the best service in achieving high water quality as well as eliminating flood issues especially in urban areas. The performance of this system was compared with common BMPs system, mainly detention pond and infiltration basin (Brander et al., 2004). Based on the study, it was found that bioretention performs better because it can optimize the water to ET and increase groundwater recharge. Detention pond always creates flood problem at the downstream areas. Then, it will cause erosion at river bank and degrade the habitat and ecosystem. However, Brander et al. (2004) suggested that the clogging problem is the prime issue when dealing with the infiltration system, mainly bioretention and infiltration basin. The same issue was highlighted where the clogging problem creates a major failure of bioretention system (Le Coustumer et al., 2007; Siriwardene et al., 2007; Jenkins et al., 2010; Reddi, 2000).

Rain garden is a favorable approach system and flexible in terms of application. However, the information data such as treatment and hydraulic responses were lacking and limited for design recommendation and modeling (Good et al., 2012). For example, the understanding of depth and soil type of filter media was poorly documented (Clar et al., 2009; Le Coustumer et al., 2008). Brown and Hunt (2011) also added that bioretention was still required specifically for fill media where the depth of media kept changing depending on the condition of drainage area criterion, drainage design, and suitability of soil on the site. Besides, bioretention design was also limited to the areas which have a minor storm event (Brander et al., 2004). Thus, it can be summarized that sufficient data were required to establish the design chart for each parameter in order to make the designer easy and comfortable using the design manual or guidelines.

DESIGN ELEMENTS

Rain gardens are great if designed properly, which then can beautify cities and provide greener and healthier environments. There are six typical components found in bioretention cells:

I. Grass buffer strips reduce runoff velocity and filter particulate matter.
II. Sand bed provides aeration and drainage of the planting soil and assists in the flushing of pollutants from soil materials.
III. Ponding area provides storage of excess runoff and facilitates the settling of particulates and evaporation of excess water.
IV. Organic layer performs the function of decomposition of organic material by providing a medium for biological growth (such as microorganisms) to degrade petroleum-based pollutants. It also filters pollutants and prevents soil erosion.
V. Planting soil provides the area for stormwater storage and nutrient uptake by plants. The planting soils contain some clay which adsorbs pollutants such as hydrocarbons, heavy metals and nutrients.

VI. Vegetation (plants) functions in the removal of water through evapotranspiration and pollutant removal through nutrient cycling.

Filter zone consists of multilayer of soil, sand, and silt with the minimum of clay content in order to prevent low infiltration rate. Media depth is the major factor in controlling hydrologic performance in bioretention (Li et al., 2009; Brown and Hunt, 2009). Brown and Hunt (2009) expressed that the deeper media depths fulfilled the LID requirement in eliminating runoff volume regularly. Davis and McCuen (2005) suggested the recommended depth of filter media ranged 150– 200 mm. Clar et al. (2007) proposed the depth of 76-122 cm (30-48 inches) suitable for plant to grow. Li et al. (2009) suggested that the media depth varied from 50 cm to 120 cm. In spite of this, Hunt et al. (2006) proposed 1200 mm depth which was deeper filter depth that allows more water seep through into the system. They also continued the study at parking lot constructed filter media with 0.9 m and 0.6 m depth, respectively. The findings achieved the objectives whereby the deeper depth provides better performance which promotes more storage volume (Brown and Hunt, 2011). Besides, the deeper filter media allow higher amounts of runoff volume to be treated. A study in Australia also recommended the deeper depth of filter media in the range of 40-200 cm deep layer (Blecken et al., 2010b). However, deeper media might increase excavation cost and also disturb the groundwater level that resulted in the failure of bioretention system (Li et al., 2009; Brown, 2011). Recently, a preliminary study was carried out using small soil column (74 mm diameter with 1 m height) to differentiate the influence of depth in nutrient treatment. The results indicated that total phosphorus (TP) can be removed with optimum depth of 400 mm (>70%) while total nitrogen (TN) only captured 30-50% removal (Takaijudin et al., 2015). Thus, it can be summarized that the range of filter media depth is 0.15-1.2 m which depends on the contribution area.

Table 1. Recommendation media depths in several technical guidelines.

Guidelines	Country	Recommended filter media depths
Low Impact Development: Urban Design Tools (LID, 2007)	Maryland, USA	1. recommended minimum depth of 600 mm to 760 mm without large tree plantings 2. if shallow rooted plants are used, soil depth may be reduced to 460 mm 3. recommended depth of 1200 mm to 1400 mm with large trees
North Shore City Bioretention Guidelines (North Shore City, 2008)	New Zealand	500 -1000 mm depth (minimum 300 mm for shrub and grass and maximum 1000 mm for trees
WSUD Engineering Procedures (Melbourne Water, 2005)	Australia	1. Lined biofiltration system with submerged zone 300 -500 mm 2. Standard lined biofiltration system 400 – 700 mm
Bioretention Manual (The Prince George County, 2009)	North Carolina, USA	Min 18" (458 mm)
Engineering procedures for ABC Waters Design Features (PUB, 2011)	Singapore	Similar standard as recommended by FAWB (2009)
Stormwater Management Manual for Malaysia (MSMA) (DID, 2012)	Malaysia	450 -1000 mm for both permeable and impermeable bioretention systems

Vegetation or plant zone is a component that makes bioretention differ from other BMPs. Selected vegetations are planted on top of the soil media to uptake some nutrients and heavy metal from stormwater runoff (Bachmann, 2006). This biological process is called phytoremediation. It also depends on regional climate trends. This is the challenge in the development of bioretention where the characteristics of plants in removing nutrient and heavy metals are limited. It is functioned to remove some of the pollutant loads and transform it to be their nutrient through transpiration and biological uptake processes. It also encourages ET and offers a pleasant site (Davis and McCuen, 2005). In addition, presence of vegetation also assists in maintaining hydraulic capacity and reducing clogging problem due to creation of macropores by root growth (Hatt et al., 2008). It takes a time longer than 4 hours to observe the performance of soil and vegetation (Asleson, 2009). It was found that the increment of plant densities has increased the performance of bioretention. Plant root enhances the permeability of soil mixture. In terms of water quality benefits, there is little information on pollutant removal by plant uptake. Clar et al. (2007) verified that the roles and types of plant suitable for bioretention were poorly documented. However, they found that the increment of plant densities had increased the performance of bioretention. Davis and McCuen (2005) stated that the selected vegetation is able to live in wet and dry conditions. Good plant can resist any high concentration of pollutants and is capable of living in various temperatures. Rain garden plant might be different from wetland vegetation because wetland required irrigation during dry period (Bachmann, 2006). In other words, the vegetation plays an important role in removing contaminants in storm water runoff. Plant root was identified to enhance the permeability of soil mixture (Clar et al., 2009). Besides, roots and shoots had capabilities to absorb metal significantly (Blecken et al., 2010a). Different plants have different needs for their growth. Thus, proper selection of vegetation must be considered to ensure that the potential pollutants can be removed effectively by the selected plants.

Another design characteristic that needs to be considered is ponding depth. This element is essential to determine the hydraulic loading of surface runoff that can be treated. This was supported by Li et al. (2009) that higher hydraulic loadings can be managed with greater ponding depth (Li et al., 2009). By having a greater ponding depth, surface area of facilities can be minimized within 25-50% reduction-cost reduction. However, little guidance on the technical basis for ponding depth was reported. Besides, approximately 152.4 cm ponding depth with 48 hr dewatering was recommended (Clar, 2007). Moreover, Palheygi (2010) suggested about 0.6 m depth can accommodate 64 m^3 ponding volume. For 100% imperviousness of drainage areas, storage were needed up to 5-10 cm with 12-25% catchment areas. It can be concluded that ponding depth depends on the drainage area size and also hydraulic loading that enters the system. Thus, according to the literature, the recommended ponding depth should be less than 1 m which can optimize the cost of excavation and provide less maintenance.

HYDROLOGIC AND HYDRAULIC PERFORMANCE

Bioretention is typical LID practice to adopt natural hydrologic process, pollutant removal and aesthetics values (Brown and Hunt, 2011). Bioretention offers multiple solutions in dealing with stormwater runoff. Based on the criterion of this system, it can provide the best service in achieving high water quality as well as eliminating flood issues especially in urban areas. The main element of rain garden is to minimize stormwater runoff volume. Heasom et al. (2006) also agreed that bioretention is the best storm water solution to minimize the impact from urbanization (Heasom et al., 2006). It can serve some advantages compared to other BMPs techniques. For example, bioretention was effective in reducing runoff volume in earlier stage before it reached the receiving nearest stream. Rain garden system shows its capability in lowering runoff volume through some physical processes such as infiltration, exfiltration and ET (Brown and Hunt, 2011). Thus, it promotes natural hydrological cycle by having those processes. However, flooding always occurred at downstream areas where detention ponds were applied. Thus, erosion occurred at river bank and lastly degraded the habitat of aquatic life (Brander et al., 2004). In some regions, bioretention was the preferable approach and had a high demand due to its versatility and level of performance. It can also reduce runoff volume through ET and exfiltration which promote natural hydrological processes (Brown and Hunt, 2011). The phases of hydrologic process was described schematically by Akan (2013) as illustrated in Figure 1. Phase I began with the runoff starting to access into infiltration structure (Figure 1a). The water starts to infiltrate at the thickness of *z*. In Phase II, the water starts to become fully saturated at the entire depth in ponding condition (Fig. 1b). The outflow was observed during this time. Figure 1c shows Phase III where the inflow and ponding depth are reduced quickly before the system is fully saturated. At this stage, no filtration access into the system at the top layer and outflow will occur. In the final phase, the saturated zone occurs at the bottom layer. In this stage, the inflow stops flowing to the system and no ponding depth occurs. The water is drained to the outlet as soil water.

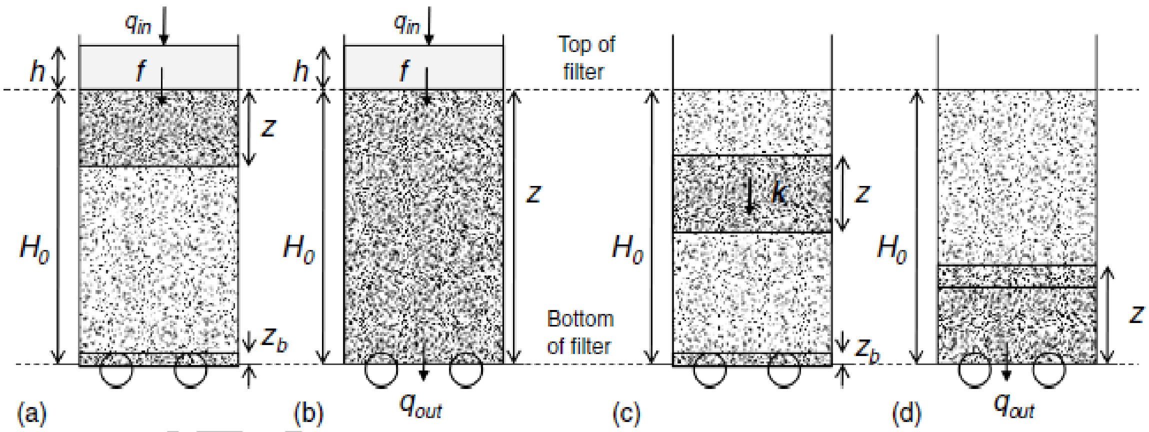

Fig. 1. The hydrologic process in bioretention system (Akan, 2013)

Bioretention system is designed to attenuate peak flow and runoff volume. There are many studies that have investigated the performance in minimizing peak flow and runoff volume. Total outflow was reduced by the unlined bioretention cell to the drainage link. In a one-year observation, less than 50% runoff volume entered the bioretention cell. It was expected that some of it would be exposed to the exfiltration and ET. Declination of outflow was important for pollutant removal computation (Hunt et al., 2006). Besides, seasons and weather also influenced the outflow volume of the cell. Ratio outflow/inflow was lower during warm seasons in comparison to winter because mass removal depends on the inflow and outflow where the removal rates are much lower during the winter season than warm seasons (Hunt et al., 2006). One bioretention technology which is called Filterra (36ft^2) can treat 90% runoff volume from 0.25 acres of catchment areas (Coffman and Siviter, 2007). By comparing with previous research, all cells achieved 70-99% peak reduction compared to Davis (2008) only 30-42% Li et al. (2009). In this study, approximately 19% of inflow to ET and another 8% contributed to exfiltration in the first cell. Another cell lost runoff volume by 19%, exposed completely to ET.

On the other hand, biofilters were effective in peak flow reduction by at least 80%. Inflow volume either from small to medium storm was a major contribution in the retention of water (Hatt et al., 2009). The types of development and the combination of both BMPs systems such as the integrated system of cistern and bioretention will enhance the hydrologic performance, i.e., peak runoff and volume flow rates vary from 50-90% (Gilroy and McCuen, 2009). Yang et al. (2009) introduced biphasic rain garden which consists of aerobic and anaerobic partition capable of eliminating 70% peak flow and 42% runoff volume. One year later, one study was carried out to show that having more soil mixtures might reduce peak discharges significantly (Carpenter and Hallam, 2010). The planting soil mixtures were tested in different compositions by adding topsoil into soil media. It was found that the mixture of 20% organic compost, 50% sand and 30% topsoil cell obtained a higher percentage in peak flow reduction (mean of 85-98%) than the 80% compost and 20% sand cell (mean 16.5-93%) peak flow reduction for all three simulated event conditions. Thus, it was indicated that the cell can perform in eliminating peak flow in 24 hours before the next storm event. Another development was by adding shredded newspaper as filter layer in filter media depth (Stander and Borst, 2010). The presence of the carbon can enhance denitrification process in bioretention system (Yang et al., 2009; Stander and Borst, 2010). Besides, it also influenced volume and flow rates. However, it was not a major factor contributing to blocking drainage. Other factors may influence impeding drainage: geotextile wrapped around pipe, stormwater solids loading, clay particle in the media (Stander and Borst, 2010). Existence of clay in the media might retain more water which make the flow in the outlet slower. DeBusk et al. (2011) observed the behavior of outflow to see whether it is similar to natural nonurban stream condition. The study suggested that some portion of bioretention outflow which is referred to infiltrated water became as shallow interflow due to infiltration, and it was the key factor in the performance of bioretention. The result indicated that there was no statistical difference between streamflow and bioretention outflow in 24 hours and 48 hours. Thus, it revealed that bioretention behaves similar to nonurban watershed process and releases streamflow in the same manner as well (DeBusk et al., 2011b). Other studies focus on the influence of the filter depth. Brown and Hunt (2011) found that 0.9m deep meets the LID goal (44%) most frequently compared to 0.6m deep which is only 21%. The declination of runoff volume influenced the reduction of pollutant loads such as TN and TP. In 0.6m and 0.9m depth of filter media, approx. 31% and 42% runoff was removed from potential outflow. Higher estimated ET and exfiltration occurred in 0.9m depth due to the large amount of storage volume. Exfiltration influences the reduction of runoff volume. Thus, the author agreed that bioretention system showed higher hydraulic performance which has the capability of minimizing peak flow and surface runoff volume, and it was even set up with different configurations as highlighted by the literature.

INFILTRATION PRACTICES

Bioretention offers infiltration process as the main process in treating urban stormwater runoff. The infiltration process in bioretention helps in reduction of stormwater runoff which is applicable for any type of development (Brander et al., 2004). A low or high infiltration rate is the indicator of the bioretention or other infiltration system performance. Davis and McCuen (2005) stated that flooding may occur when the system failed and has low infiltration rates. Clar et al. (2007) stated that this infiltration practice which was implemented at existing ground was under utilization by many local criteria for ponding depth.

The infiltration process was influenced by large numbers of factors. The main factors are soil characteristics, surface condition, fluid characteristics and soil compaction. Soil characteristics, mainly grain size, might affect the soil water movement and water retention (Nestor, 2006). Moreover, different types of soil also influence the infiltration sensitivity. For example, loamy sand provides higher infiltration performance compared to silty clay (Brander et al., 2004). Physical feature of soil, mainly grain size, is the most important to enhance the infiltration process. The particle size in the range of 0.075-2 mm was recommended. Inappropriate selection of grain size particle might lead the BMPs system under or over design which contributes to the ineffective cost (Selbig, 2013). The accumulation of fine sediment may limit the rain garden's design life (Jenkins et al., 2010). Besides, particle size distribution (PSD) was less uniform and wider range of particle size due to having larger Coefficient Uniformity (C_U) (Stander and Borst, 2010). The grain size distributions were measured by particle size analyzer (Cho et al., 2009). Normally, sieve analysis is used to determine PSD for sand materials where hydrometer analysis for silt and clay materials is conducted. Larger grain sizes create more pores through which water can seep quickly. However, there is little treatment since some sediments or chemical substances can also pass through the porous media. On the other hand, the presence of clay content in soil media also influences the infiltration performance. This was highlighted by previous researches and they also provide the maximum content of clay which is less than 25% (Carpenter and Hallam, 2010; DID, 2012). However, FAWB (2009) recommended that the clay and silt content should be less than 3% to prevent structural collapse of the soil. Besides, two study sites were conducted in North Carolina which consisted of clay soil. Based on this study, it was found that the two sites have low permeability rates of 1 and 2.1 cm/h, respectively due to the presence of higher amount of clay (Brown and Hunt, 2009). Thus, most of the literature suggested that filter media must be used for engineering soil which consists of topsoil, organic compost and topsoil to increase the treatment performance.

The composition of soil also affected the infiltration process. Sand was the main media added into bioretention system to enhance saturated hydraulic conductivity (K_{sat}) (Grebel et al., 2013). Compost is one of the main components in soil mixtures. It was used for plant growth and enhancing soil capability. It was believed that compost material is capable of providing microbial populations which allow more microbial activities and supply carbon source, nutrients and moisture (Alcala et al., 2009; Ahmad et al., 2011). However, extra care is needed when dealing with compost since it can cause nutrient leaching (Lim et al., 2015). Common range of soil mixtures was 30-60% of sand, 20-40% of compost and 20-30% of topsoil. A soil column experiment was conducted to measure soil properties (i.e., bulk density, moisture capacity, K_{sat} for various soil mixtures: sand (30%-70%); silt loam or sandy soil (0%-20%), and (20%-70%) compost. They found K_{sat} of maximum compost range (1359-1261 mm/hr) while minimum ranges were 784 -997 mm/hr (Thompson et al., 2008). A similar study was continued by Paus et al. (2014) to investigate the influence of compost fraction volume (CVF) ranged 0-50% on K_{sat}, heavy metal and phosphorus treatment. They found that the declination of K_{sat} was observed by increase of CVF.

Another study compared the hydraulic parameters such as runoff volume, peak flow reduction and infiltration rate for 2 different soil mixtures, which were 20% compost, 50% sand, and 30% topsoil and 80% compost and 20% sand. The result showed that permeability rate was higher for the soil composed of 80% compost and 20% sand due to more macropores created in the soil as compared to 20% compost, 50% sand, and 30% topsoil (Carpenter and Hallam, 2010). The result showed the presence of compost produce lesser K_{sat} with higher field capacity due to improper mixing than without compost. It provides higher porosity. The absence of compost in soil mix provides less water retention (40%) compared to the presence of compost caused by high infiltration rates generating more outflow to the underdrain. FAWB (2009) have listed the soil mixtures according to the (PSD) whose main media are sand (up to 60%), about less 3% of clay and gravel. DID (2012) also followed the same figures with 20-25% of topsoil, 50-60% of medium sand and 12-20% of leaf compost. Wide variations of soil mix provide difference infiltration rates, and it will lead to high cost of construction (Coffman and Siviter, 2007). The mixtures of 60% sandy loam, 20% compost and 20% mulch layer helps to maintain the infiltration capacity due to the inherent high porosity of filter media as well as cracking and the creation of macropores during dry periods (Hatt et al., 2008).

Several studies were conducted for both laboratory work and fieldwork to examine the infiltration parameters for bioretention. In 2007, the hydraulic performance was examined through column study and 40 constructed biofilters at New South Wales, Victoria and Queensland (Le Coustumer et al., 2007). From the study, it showed that the soil specification was significant to determine earlier because the different characteristics of soil might bring a significant difference in infiltration parameters mainly K_{sat}. In Korea, six columns were set up with different arrangements of combinations of fine and coarse soil layer and hardwood mulch layer. Coarse sand was selected due to its characteristics in providing rapid infiltration. The treatment process occurred at this layer when fine sand layer was fully saturated. Fine soil was used to improve adsorption and biodegradation process (Cho et al., 2009). Another column study was conducted at North Carolina, USA to observe the impact of clogging and bacteria removal in bioretention system. The average seepage rate of bacteria-free stormwater column was reduced 50% after 11 trials. Bacterial aggregation between sand's pore spaces occurred in bacteria-spiked stormwater column which affect the reduction of infiltration during the design phase of sand filter, and large amount of bacteria accumulated at sand surface layer may occur (Bright et al., 2010). Interaction of infiltration rates with bacteria removal through lab experiment use the sand column. It showed a seepage rate reduced significantly due to the volume of sediment in storm water runoff-accumulate on sand layer which resulting clogging problem and decreasing seepage rate (Bright et al., 2010; Siriwardene et al., 2007). Recently, fly ash was used as a material in filter media which mixed with sand to enhance infiltration process (Chavez et al., 2013). The three-dimensional (3D) finite element model called COMSOL found that the presence of fly ash in filter media provides complicated flow. The variance of K_{sat} was increased by 5% or less. Table 2 lists the variation of soil materials that have been used in bioretention system with K_{sat} based on previous studies.

Table 2. Comparison of K_{sat} for selected soil materials applied in bioretention systems (Note: SL: sandy loam; M: Mulch; C: compost, T: Topsoil)

Author (year)	Soil materials	K_{sat} (mm/hr)
Brander et al. (2004)	Loamy sand	30.5
Davis and McCuen (2005)	sand, loam and clay	
Hunt et al. (2006)	Clay loam	5.04-15.12
Le Coustumer et al. (2007)	Media 1 (SL, vermiculite and perlite); Media 2 (SL with low pH, mulch and compost); Media 3 (sandy loam, mulch and compost)	367 ± 193 (Media 1) 115 ± 40 (Media 2) 393 ± 84 (Media 3)
Clar et al. (2007)	Loamy sand or sandy loam	13.21 (sandy loam) 210 (sand)
Estes (2007)	sandy clay (37-49% clay, 25-27% silt, 24-30% sand)	
Hatt et al. (2008)	60-80% SL, 10-20% M and 10-20% C	216-360 (*80SL:10M:10C) 5760 (60 SL:20M:20C)
Li et al. (2009)	sandy loam and loamy sand	
Bright et al. (2010)	Dune sand with 0.6% silt	
Jenkins et al. (2010)	coarse sand	
Palhegyi (2010)	Sandy loam with 46% porosity	51-76
Blecken et al. (2010b)	sand layer with 5% silt and 14% fine gravel layer, top soil 100 mm; medium to fine sand at bottom layer.	
Carpenter and Hallam (2010)	100C/0S/0T	183.9
	0C/100S/0T	259.8
	0C/0S/100T	16.8
	80C/20S/0T(field)	466.1
	80 C/20S/0T(lab)	455.9
	20C/50S/30T(field)	20.3
	20C/50S/30T(lab)	46.7
	50C/50S/0T	55.4
	35C/65S/0T	70.4
Good et al. (2012)	System 1 (500 mm sand); System 2 (500 mm topsoil); System 3 (250 mm both sand and topsoil)	800±5 (System 1) 160±2 (System 2) 290±5 (System 3)

K_{sat} is the main parameter in infiltration system. This parameter indicates the performance of infiltration process in bioretention system. The standard method of permeability test can determine the K_{sat} by varying the type of soil. K_{sat} can be determined using either direct or indirect method. Darcy Law can be applied to all situations except for soil which had low porosity and low hydraulic gradient. Darcy Law applies for the flow of water through unsaturated soil but K_{sat} is a function of saturation and void ratio of soil (Masrouri et al., 2008). K_{sat} is 3 to 4 times infiltration rate due to the presence of macropores. Similar concept of constant head method which applied Darcy Law equation was implemented in column studies in measuring K_{sat} (Good et al., 2012; Paus et al., 2014; Thompson et al., 2008; Lucas and Greenway, 2011).

The challenges in dealing with K_{sat} was that the monitoring process was time consuming (Candemir and Gülser, 2012). Hence, pedotransfer (PTFs) model (Candemir and Gülser, 2012; Bayat et al., 2015) was recommended to predict the response of soil properties on K_{sat} in fine-textured alkaline soils.

If macropores exist, the water has low

quickly, but when macropores are full of water, the flow becomes slow and nearly reaches steady state (Brown and Hunt III, 2010). A laboratory study was conducted to observe the interaction between K_{sat} and pore pressure. The results indicated that the excess pore pressure was highly correlated with the logarithm of K_{sat} for both relative densities (D_r) (R^2=0.99 for D_r=20% and R^2=0.92 for D_r=91%) in the soil mixtures (Belkhatir et al., 2013). Sand plays a significant role in retaining high permeability where it must have d_{10} at least 0.6mm (Davis and McCuen, 2005). However, a higher permeability rate does not reflect the better performance of bioretention. It is because it will lead to more outflow discharged as untreated water. A comprehensive study was conducted in Melbourne, Australia to enhance the hydraulic performance in biofilters. It was indicated that median K_{sat} = 88mm/h which is a value consistent with Australian design guidelines (50-200 mm/h). K_{sat} in testing column is significantly reduced over time. It dropped drastically in the first four weeks of testing and then became constant in one value with overall reduction of 66%. Overall, the ratio of catchment area to biofilter size and soil types were the main contributor to the progression of K_{sat} (Le Coustumer et al., 2007). The systems with low initial K_{sat} produce less impact of clogging as compared to systems with high initial of K_{sat}. This is because the finer particle size distribution will be more comparable to the inflow sediment. One strategy can be applied as contingency factor in specification of K_{sat} value. For example, if the design required using soil media with 180 mm/hr, 50% of design value (90 mm/hr) need to be used for sizing purposes. Over-sizing assisted to 'buffer' against unintended reduction in K_{sat} (Le Coustumer et al., 2008).

Filter media depth is also the key indicator of the bioretention performance. However, deeper media might increase excavation cost and also disturb the groundwater level that resulted in the failure of bioretention system (Li et al., 2009). It was suggested by the annual water budget analysis that approximately 20–50% of runoff entering the bioretention cells was lost to exfiltration and ET. According to field study at Nashville, North Carolina, the researcher found that the deeper fill media offer more exfiltration and minimum outflow (Brown and Hunt III, 2011). This study monitored two loamy-sand bioretention cells with 0.6m and 0.9m depth, respectively. Based on the research, they compared water balance for both cells where the exfiltration of 0.9 m cell was up to 39% greater than 0.6 m depth which is only 28%. The outflow for cell with 0.9 m depth was lower (23%) than the cell with 0.6m depth (32%). However, the ET and overflow were approximately the same. Exfiltration have influenced the reduction of runoff volume.

Any infiltration practices might be exposed to clogging problems (Brander et al., 2004). This issues is also highlighted by Siriwardene et al. (2007) where the filtration system becomes a failure due to clogging. They added that it will shorten design lifespan and make the system not function if there was poor maintenance of filtration system. Thus, higher amount of overflow was untreated water. In addition, Hatt et al. (2008, 2009) stated that this is the prime issue for an infiltration system which contribute to failure of the system such as overflow; extended ponding time, decreased treatment efficiency, and aesthetic problem. About 43% of biofilters had K_{sat} less than 50 mm/h due to clogging problem and insufficient design of original fill media. The presence of vegetation will minimize clogging issues due to the formation of macropores by root growth and senescence. It may clog void space of the soil mixtures, so the infiltration capacity will decline and result in low performance of rain garden. Approximately 65-75% runoff that carried sediments was retained in SCM. Deposition might clog the pore spaces, so it may minimize the space for water to retain in SCM as well as the infiltration process. Thus, maintenance such as raking or stripping the top soil was needed (Jenkins et al., 2010). Accumulation of sediment at filter surface causes decline in hydraulic performance. The media with higher K_{sat} experienced the clogging problem less (Hatt et al., 2008). An experiment using sand column showed that the seepage rate was reduced significantly due to volume of sediment in storm water runoff and its accumulate on sand layer which resulted in the clogging problem and the decrease of seepage rate (Bright et al., 2010). Hence, safety factor of 2 was recommended to design bioretention system where clogging was taken into consideration. However, this safety factor was randomly used which might be different. No significant study was conducted to observe the evolution of K_{sat} over time (Le Coustumer et al., 2009).

The successful of filtration system is also affected by surface condition. It is recommended that a variety of infiltration practices be implemented based on the site condition rather than having a small amount of best practices which is applied for the whole areas (Brander et al., 2004). Moreover, the urban cluster development provides lowest runoff volume due to its having a large open space which encourages more infiltration process naturally. Estes (2007) compared the infiltration rates for pre-development and post-development condition. The results found that the infiltration rates were higher in pre-development condition in the range of 6.1-80 mm/hr which for post-development was only 1.4-7.5 mm/hr. It can be summarized thus: by having more impervious area, the infiltration process significantly dropped, and this condition will eliminate this process in the long term period (Estes, 2007). Besides, the runoff from two asphalts parking lot areas at Louisburg were treated by bioretention up to 77% and 82% runoff, respectively, due to rapid infiltration. It shows that infiltration is one of the main indicators in design consideration (Li et al., 2009). A constructed rain garden at Villanova campus at southeastern Pennsylvania which received stormwater runoff from nearby parking lots was investigated. It was found that the infiltration rate was still high even though some locations are exposed to the sediment deposition. Along the perimeter drain, mean infiltration rates ranged 4.1-65 mm/h. While at the middle SCM, the mean infiltration rate is 58.3-255mm/h. It was observed that the fines were deposited mainly at the entrance, hence the infiltration rate at the entrance was lower (Jenkins et al., 2010). Spreading runoff onto compacted lawns seems not efficient compared to uncompacted lawns due to the pore areas becoming smaller which allows low infiltration rates (Brander et al., 2004).

Besides, fluid characteristics are also important in determining infiltration parameters. As we know, stormwater carried a variety of pollutants including bacteria. There is a reduction of the seepage rate due to sediment present build up over time (Bright et al., 2010). Ripening phenomena where water passes through media filter, water born microbes are removed as they deposit on the filter media. Reduction of deposition rate of bacteria is affected by large bacteria loading which lead to high coverage of the soil surfaces. On the other hand, another study suggested that some portion of bioretention outflow which is referred to as infiltrate water and became as shallow interflow due to infiltration, was the key factor in the performance of bioretention (DeBusk et al., 2011a).

Soil compaction was another issue that needed to be taken into account especially during the construction stage. There was a little concern on excavation techniques and soil-moisture condition during construction

(Brown and Hunt III, 2010). Both elements might produce higher level of compaction which result in lower infiltration capacity. This condition was approved by their study on two common excavation techniques; rake and scoop method, under a variety of soil-moisture conditions. They concluded that rake method provides a better approach due to less compaction and being able to enhance soil properties related to infiltration. In addition, this method offers more pore space creation by having a lower bulk density and promotes an exfiltration process in underlying soil in-lined with the main function of a bioretention system (Brown and Hunt III, 2010). Compaction has caused the reduction of infiltration rates particularly in urban construction sites. There was little concern on excavation method during construction. Rake method generated infiltration rate and K_{sat} higher due to lower levels of soil compaction and low bulk density which encourage the water to move quickly in the soil (Brown and Hunt III, 2010). K_{sat}, infiltration rate and bulk density will be greater using rake method under dry conditions due to lower content. K_{sat} was reduced for soil-based media except sand media due to compaction of filter media with high correlation (r^2=0.96) ranged 6-10x10-5m/s (Hatt *et al.*, 2008). High level compaction on soil filters may reduce their capability in discharging water unlike sand filter. Thus, it was important to consider compaction method during construction work. In addition, there was a lack of field data available on the sustainability and long-term performance of biofilters. Possible compaction or disruption of soil during the ring was driven into the soil (Le Coustumer et al., 2008). Possible compaction and disturbance of soil during the ring driven might influence the result (Le Coustumer et al., 2009). Only hand-light compaction should be used to make consistency on construction method and with typical construction of biofilters (Le Coustumer et al., 2012). Other studies reported that denser fine-textured soil might be exposed to the larger changes on hydraulic properties which tend to have lower K_{sat} and higher porosity (Benson et al., 2007). Hence, extra care is needed during construction stage and also experimental work. The compaction must be consistent for each layer of media.

TREATMENT PERFORMANCE

Rain garden can be considered as a multi-functioned system where it is not only assisting in flow attenuation and storage facilities, it is also capable of removing pollutants such as nutrients and bacteria (Blecken et al., 2010b). Besides, this system can minimize runoff pollutants in several processes including infiltration, adsorption, biodegradation, phytoremediation and others. Surprisingly, it can also remove bacteria through biological processes (Bright et al., 2010). Moreover, it has the potential to assist in groundwater recharge and enhance evapotranspiration.

Bioretention has shown impressive pollutant removal through laboratory studies in the reduction in concentration of phosphorus (70 to 85%) and ammonium (60 to 80%) (Davis et al., 2006). Another study also showed that the selection of filter media plays an important role in removing pollutants especially nitrogen and phosphorus (Hsieh and Davis, 2005; De Busk et al., 2011). Many comprehensive studies were carried out to foresee the effectiveness of bioretention as a pollutant removal. Theoretically, bioretention is the preferable approach due to having accurate mass removal efficiencies for BMPs. Hunt et al. (2006) conducted a research on three field sites of North Carolina which implemented the bioretention system (Hunt et al., 2006). The different characteristics of the cells in term of drainage configuration, fill media design, soil permeability, precipitation and seasonal factor were studied, and it was found that it might influence the pollutant removal as well as annual pollutant loads (Hunt *et al.*, 2006). Water samples were collected at three cells; G2, C1 and G1 at different sites. It was discovered that approximately 40% annual total nitrogen (TN) mass was removed at two conventional underdrain (G2 and C1) of rain garden. Total phosphorus (TP) was significantly removed at G2 with range 65-240%. Besides, P-Index was the highest at G2 compared to other cells about 86-100 which indicated that the media was saturated with phosphorus (P).

Laboratory column studies offer the ability to segregate contaminant particulates and simulate variation treatment process (Liu et al., 2016). In 2007, the researchers set up column studies to observe the performance of nutrient removal (Blecken et al., 2007). They assessed 15 biofilter columns in treating synthetic runoff at low temperatures and found that biofilters performed well in eliminating TP. Dissolved P was also removed well by biofilters. However, it was not dependent on temperatures. Mechanical removal was the main factor in dissolved P removal. Conversely, the results showed that poor performance occurred in removing TN due to high leaching and lacking of denitrification process. After three years, they carried out the same studies on the impacts of low temperatures on biofilters performance. However, similar trends were found where the systems were effective in removing phosphorus and total suspended solid (TSS) with efficiencies removal 90% and 95% respectively. It was stated that removal of phosphorus at higher amounts was significant because it might cause euthrophication especially during winter where the oxygen level became lower under ice layers. In addition, TN leaching was identified in this study due to nitrogen gas (NO_x) production which leads to high nitrification in warm temperatures (Blecken et al., 2007).

The integration of detention pond and biofilters provided higher performance in treating stormwater runoff for large scale of catchment areas. A modeling study using Source Loading and Management Model (SLAMM) was applicable to simulate pollutant loadings from different types of land use impervious to the vegetated areas (Hurley and Forman, 2011). Studies showed approximately 62-79% of TP was removed by detention pond. Besides, the highest removal was 55-71% using biofilters which incorporated with subdrains whereas biofiltration without underdrains was performed well in achieving TP removal exceeding 65% (Hurley and Forman, 2011). Another investigation was carried out by Brown and Hunt (2011). The cells were observed less efficient in removing the nutrient particularly TN and TP. The range was 19-21% removal for TN and 10-44% for TP. Overall, biofilters show better performance in TP removal, but they need further improvements in nitrogen removal.

Bioretention cell was effective in removing heavy metals. In a period of one year, more than 98% of Zinc (Zn) and Cuprum (Cu) mass rate were removed through the system, while plumbum (Pb) removal rate exceeded 80% (Hunt et al., 2006). The existence of submerged zone significantly changed the heavy metal concentration reduction in outflow. It was reported that about 95-98% of removal efficiencies existed in biofilters with submerged condition compared to one without submerged condition which is roughly 80-90% respectively (Blecken et al., 2009). In addition, the integration of carbon source and submerged zone was helped in Cu removal up to 97%. Similar studies identified impacts of cold climate to the removal rate of heavy metal particularly Cu. A biofilter mesocosms study highlighted that the effluent metal concentration was reduced significantly compared to those with influent concentration (Blecken et al., 2010a). Nevertheless, ANOVA statistical analysis explained that the different temperatures did not relatively influence heavy metal removal excluding Cu removal. Cu was slightly affected by temperatures because the concentration was observed to be increased as the temperature was increased (Blecken et al., 2010a).

One research in 2011 showed that there was a reduction of annual pollutant loads with different filter media depth. Both 0.6 m and 0.9 m depth filter media were performed better in removing TSS approximately 71% and 82%, respectively (Brown and Hunt III, 2011). Jenkins et al. (2010) studied the influences of fine accumulation in rain garden cell. About 54 m^3 excavated natural soil was replaced by course sand with various particle sizes ranged 0.075-2 mm where this soil composition was expected to provide higher seepage rate and K_{sat}. Two first flush samplers were used to examine TSS at the inlet and within the basin. The results revealed that approximately 88% TSS removal was achieved and mean and median were 171 mg/L and 74 mg/L, respectively. By having the varied size of course sand, about 65-75% runoff that carried sediments were retained in rain garden cells (Jenkins et al., 2010). Conversely, deposition might clog pore spaces and minimize the space for water to retain in SCM as well as the infiltration process. Hence, maintenance such as raking or stripping the top soil was needed. Furthermore, TSS removal was not significantly affected by temperature. It was removed by physical filtration process which depend on infiltration rates and arrangement of fills media (Blecken et al., 2007). Besides, other studies examined various plant capabilities to capture nutrient contaminant. From the study, they found that P and N had lower concentration in vegetated compared to non-vegetated soil (Read et al., 2008). Twenty biofilters were designed to evaluate nutrient treatment performance under design modifications (vegetation and saturated zone; Glaister et al., 2013). They found that a vegetated biofilter with skye sand and a saturated zone performed very well in capturing nitrogen and phosphorus during wet and dry seasons. On other parameters, the biofilters achieved well performance in treating chemical oxygen demand (COD), biological oxygen demand (BOD), ammoniacal nitrogen (NH_3-N) and TSS with 94, 88, 85, and 98%, respectively (Sidek et al., 2016)

Filterra ® utilized all physical, chemical process into bioretention system to treat urban storm water. It was able to provide effective water treatment where 95%, 91%, 82% and 76% of TSS, heavy metals, TP and TN respectively were removed from 0.25 acres drainage areas (Coffman and Siviter, 2007). Table 3 demonstrates the summary of pollutants removal studies in bioretention from previous researches.

CONCLUSIONS

Bioretention system is the favorable approach which can be applied anywhere from individual lot to the regional catchment area. It has potential in duplicating natural hydrological cycle because most of the processes occurred in this system but still need further investigation. The treatment and hydraulic responses for long term operation were still lacking due to insufficient information data. Hence, there was little design guidelines documented, and most of the manuals followed the specific requirements in-lined with country needs. In addition, the design components also still varied and did not have the specific standard which depended on several factors and local condition. In terms of development in bioretention, it has very well progressed since the development and amendment of the system has grown very fast recently. On the other hand, the hydraulic and hydrologic performances were discussed in detail. It was concluded that the system is able to reduce the peak flow and runoff volume effectively through some of the

Table 3. Water quality performance in bioretention system across literature.

Author (Year)	**Study Description**	**Pollutant Removal (%)**		
		TSS	**TN**	**TP**
Hunt et al. (2006)	Influence of drainage configuration on pollutant removal	170	40	65-240
Blecken et al. (2007)	treatment rate at low temperature			
	2 °C	97.5	-0.5	81.2
	8°C	96.4	-11.6	80.3
	20°C	97.5	-207.8	80.7
Coffman and Siviter (2007)	3.345 m^2 rain garden can treat runoff from 0.25 acres catchment areas	95	76	82
Bratieres et al. (2008)	Five (5) factors were examined in 125 columns: plant species, filter media, filter depth, filter area and pollutant inflow concentration	>95	70	85
Carpenter and Hallam (2010)	Soil mixtures:			
	80compost/20sand	97.9	19.9	76.9
	20compost/50sand/30topsoil	79.3	90.8	97.2
Blecken et al. (2010a)	removal at low temperature:			
	2 °C	98	-5	92
	7°C	98	-23	91
	20°C	98	-172	91
Hurley and Forman (2011)	Comparing Phosphorus removal by applying			
	i. detention ponds			62-79
	ii. Biofiltration			55-71
Erickson et al. (2012)	Stormwater treatment through iron-sand filter			88
Bakacs et al. (2013)	Car wash runoff treated by bioretention mesocosms	84-95		197-388
Barrett et al.(2013)	Column studies utilized media (concrete sand, masonry sand, medium) and plants (Buffalograss 609 ad Big Muhly)		59-79	77-94
Geronimo et al. (2014)	Two types of bioretention were compared by having different plant species		49-55	85-86
Guo et al. (2014)	Seven soil columns were tested with different soil mixtures	93.4	59.8	92.7
Houdeshel et al. (2015)	Evaluating bioretention under arid and semi-arid climate		22-50	50

hydrologic processes, mainly the infiltration process. Determination of K_{sat} is the main indicator to assist the infiltration process and it was influenced by some other factors. One of the factors was the soil composition where it helps to achieve the optimum K_{sat} and then also assist the infiltration process. It is also necessary to consider whether the infiltration process can also enhance the treatment performance not just only discharge the surface runoff. Performance of bioretention was also described well in this paper. TSS and TP were captured well through the system. However, TN removal was varied across literature since a more complex process occurred in bioretention. Thus, it was suggested that more data information can be obtained to establish design chart useful for designers and researchers in the future. Besides, the author would recommend the use of local waste materials in engineered soil also relevant and practical be implemented in bioretention system.

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